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Debris-covered Himalayan glaciers under a changing climate: observations and modelling of Khumbu Glacier, Nepal

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Many mountain glaciers are characterised in their lower reaches by thick layers of rock debris that insulate the glacier surface from solar radiation and atmospheric warming. Supraglacial debris modifies the response of these glaciers to climate change compared to glaciers with clean-ice surfaces. However, existing modelling approaches to predicting variations in the extent and mass balance of debris-covered glaciers have relied on numerical models that represent the processes governing glaciers with clean-ice surfaces, and yield conflicting results. Moreover, few data exist describing the mass balance of debris-covered glaciers and many observations are only made over short periods of time, but these data are needed to constrain and validate numerical modelling experiments.

To investigate the impact of supraglacial debris on the response of a glacier to climate change, we developed a numerical model that couples the flow of ice and debris to include important feedbacks between mass balance, ice flow and debris accumulation. We applied this model to a large debris-covered Himalayan glacier—Khumbu Glacier in the Everest region of Nepal. Our results demonstrate that supraglacial debris prolongs the response of the glacier to warming air temperatures and causes lowering of the glacier surface in situ, concealing the magnitude of mass loss when compared with estimates based on glacierised area. Since the Little Ice Age, the volume of Khumbu Glacier has reduced by 34%, while glacier area has reduced by only 6%. We predict a further decrease in glacier volume of 8–10% by AD2100 accompanied by dynamic and physical detachment of the debris-covered tongue from the active glacier within the next 150 years.

For five months during the 2014 summer monsoon, we measured temperature profiles through supraglacial debris and proglacial discharge on Khumbu Glacier. We found that temperatures at the ice surface beneath 0.4–0.7 m of debris were sufficient to promote considerable amounts of ablation. Moreover, although temperatures within the debris layer decreased with depth at the start of the monsoon, later in the monsoon season thicker debris (0.7 m) appeared to retain more heat close to the glacier surface than thin debris (0.4 m). Remote sensing observations indicate that Khumbu Glacier is losing mass more rapidly than is predicted by our model, particularly as ice cliffs and supraglacial ponds enhance ablation locally, and our field observations suggest an additional mechanism for enhanced mass loss.